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Approximate Analytical Formulae for Electron Density and Collision Frequency in the Natural and Nuclear-Disturbed Ionosphere and Inner Magnetosphere

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The phenomenological models of global electron density for the natural ionosphere of Ching and Chiu (1973) and Chiu (1975) have been extended to both lower (60 km) and higher (36,000 km) altitudes. Computer simulations of a high altitude nuclear explosion are analyzed to develop a phenomenological model of electron density. Approximate analytical formulae for electron density and associated electron collision frequency in both the natural and nuclear-disturbed near earth space plasma environment are derived. Keywords)

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APPROXIMATE ANALYTICAL FORMULAE FOR ELECTRON DENSITY AND COLLISION FREQUENCY IN THE NATURAL AND NUCLEAR-DISTURBED IONOSPHERE AND INNER MAGNETOSPHERE

I. INTRODUCTION

Radiowave propagation through the natural and nuclear-disturbed space environment has been the subject of intense study over the last several decades [see, for example, Budden, 1966; Davies, 1966; Cornwall et al., 1981, and references therein]. It is well known that these environments can lead to refraction, reflection, and absorption of radio waves propagating in and through these regions. Two fundamental quantities needed to assess the impact of the atmosphere, ionosphere, and magnetosphere on radio wave propagation are the electron density and electron-ion collision frequency.

Much effort has been devoted to the development of models of electron density in the earth's ionosphere [Kohnlein, 1978 and references therein]. Several experimental tools, e.g., ionospheric sounders, satellites, incoherent scatter radars, have been used to both generate and validate these models. The density models developed thus far can be most easily classified as either phenomenological, empirical, or physical. The Bent model [Bent et al., 1972; Llewellyn and Bent, 1973], which is a purely phenomenological electron density model covering the altitude range from about 150 to 1000 km, was developed from ground station observations, F_2 peak layer models, and satellite measurements. The principal goal of the Bent model is to maximize, on a global scale, the accuracy of the determination of the total electron content.

Ching and Chiu [1973] and Chiu [1975] have also developed a phenomenological electron density model which is global and is valid in the altitude range 110-1000 km. This model, which is based on a large data base of ionospheric sounding data, attempts to give analytical formulae to describe not only the large scale changes of electron density with altitude, latitude, and longitude, but also seasonal, diurnal, and solar cycle variations.

Nisbet [1970a, 1970b] has developed a physical model based upon an empirical framework of electron density of the earth's ionosphere in the altitude range 100-1000 km.

Kohnlein [1977] has developed a purely empirical model of the global morphology of electron density and its variation with space, time, and geophysical conditions which covers the altitude interval 60-3500 km and is limited to quiet geomagnetic conditions ($K_p \leq 2$).

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Thomason et al. [1979] have developed an empirical model of electron density which includes topside ionospheric variations and some high latitude ionospheric effects.

For the nuclear disturbed ionosphere, electron densities and associated quantities, e.g., electron temperature have been derived, for the most part, from computer simulations of high altitude nuclear explosions [see, e.g., Kilb, 1977 and Cornwall et al., 1981].

In this report we extend the analysis of the model of electron density for natural ionosphere of Ching and Chiu [1973] and Chiu [1975] to both lower ($\approx$ 60 km) and higher ($\approx$ 36,000 km) altitudes. In addition, we investigate the evolution of electron density derived from a computer simulation of a high altitude nuclear burst. Finally, we develop approximate analytical formulae for the electron density and associated collision frequency for both the natural and nuclear disturbed near earth space plasma environment.

II. NATURAL IONOSPHERE AND INNER MAGNETOSPHERE

As discussed in the previous section, several phenomenological or empirical models of electron density in the earth's ionosphere have been advanced in recent years. The model of Ching and Chiu [1973] and Chiu [1975] is the only model that provides analytical formulae not only for electron density as functions of altitude, geomagnetic latitude, and longitude but also for diurnal, local time, annual, and solar cycle variation. The input parameters of the model are the altitude z, the annual time t, the geographic latitude λ, the geomagnetic latitude λ_m. The local time ϕ, the monthly relative sunspot number ρ, the geomagnetic longitude l_m, and the geomagnetic dip angle δ_m. The electron density in the model of Ching and Chiu [1973] and Chiu [1975] is computed using three independent Chapman function profiles representing the E, F_1, and F_2 layers

$$N_e = \sum_{i=1}^{3} A_i H_i \left(z, \lambda_m, \phi\right) V_i \left(t, \lambda, \lambda_m, \phi, \rho\right) \tag{1}$$

with

$$H_i = \exp \left\{a_i \left[1 - \bar{z}_i - \exp \left(- \bar{z}_i\right)\right]\right\}$$

and $\bar{z}_i = (z - p_i)/h_i$ and $V_i = f_i(\lambda, \lambda_m, \rho)P_i(t, \lambda, \lambda_m, \phi, \rho) + (1 - f_i(\lambda, \lambda_m, \rho))U_i(t, \lambda, \lambda_m, \phi, \rho)$. The density for each layer is the product of an amplitude parameter A_i, an exponential Chapman profile function H, and a layer peak function V. The exponential Chapman profile function is given in terms of standard Chapman parameters a_i [Chiu, 1975], the peak layer altitude $p_i(\lambda_m, \lambda, t, \phi, \rho)$ and the scale height function h_i. The layer peak function consists of a polar function $P_i(\lambda_m, \lambda, t, \phi, \rho)$ and a nonpolar function $U_i = S_i D_i L_i T_i E_i \Lambda_i \Delta_i$ where $S_i(\rho)$ gives solar cycle variations, $D_i(\phi, \lambda_m, \rho, \chi, \delta)$ is a diurnal function with χ and δ the solar zenith angle and solar declination, respectively, $L_i(\lambda_m, \phi)$ a latitudinal function, $T_i(\lambda, \lambda_m, t, \phi, \rho)$ represents annual variation, and $E_i(\lambda_m, \phi, \rho)$ an equatorial anomaly function, $\Lambda_i(\lambda_m, l_m)$ a longitudinal function, and $\Delta_i(t, \delta_m)$ a magnetic dip function. The analytical formulae for f_i, P_i, and U_i can be found in Appendix A.

However, the analytical model of Ching and Chiu [1973] and Chiu [1975] is valid only in the altitude range 100 - 1000 km. The model severely underestimates the electron density at both D-region ($\approx$ 60 - 80 km) and topside ionospheric and inner magnetospheric altitudes ($\gtrsim$ 1000 km). We have generalized the altitudinal dependence of the electron density as derived from the model of Ching and Chiu [1973] by adding (1) an exponential variation to represent D-layer variation and (2) a power law to model topside ionospheric and inner magnetospheric variation. In this expanded model we have

$$N_e = \begin{cases} \sum_{i=1}^{3} A_i H_i V_i + A_D H_D(z) & 60 \text{ km} \le z \le 1000 \text{ km} \\ A_m H_m(z) & z \ge 1000 \text{ km} \end{cases}$$

where $A_D = 1 \times 10^2$, $H_D(z) = \exp\left[- \left|\left(\frac{z - 65}{5}\right)\right|\right]$, $H_m(z) = (1 \times 10^3/z)^3$,

and $A_m = \sum_{i=1}^{3} A_i H_i(z = 1000 \text{ km})V_i + A_D H_D(z = 1000 \text{ km})$.

We have constructed, based on this generalized model, a computer program entitled DENSITY which computes electron density as a function of altitude, geomagnetic latitude, longitude, diurnal time, local time, annual time, and solar cycle variation. Figure 1 displays a typical variation of electron density with altitude in the generalized model at three different geomagnetic latitudes. An approximate analytical functional form for the electron density as a function of altitude only in this extended model of Ching and Chiu [1973] can be expressed as

$$N_e(z) = \sum_{i=1}^{5} g_i(z) \tag{2}$$

where $g_i(z) = A_i \Lambda_i(z)$, $A_1 = 1 \times 10^2$, $A_2 = 1.36 \times 10^5$, $A_3 = 2.44 \times 10^5$, $A_4 = 6.6 \times 10^4$, and $A_5 = 1.20305 \times 10^3$ with ($60\text{ km} \leq z \leq 1000\text{ km}$)

$$\Lambda_1(z) = \exp\left[-\left|\left(\frac{z-65}{5}\right)\right|\right]$$

$$\Lambda_2(z) = \exp\left[1-\left(\frac{z-110}{10}\right) - \exp\left\{-\left(\frac{z-110}{10}\right)\right\}\right]$$

$$\Lambda_3(z) = \exp\left[1-\left(\frac{z-180}{34}\right) - \exp\left\{-\left(\frac{z-180}{34}\right)\right\}\right]$$

$$\Lambda_4(z) = \exp\left[1-\left(\frac{z-240}{L_4(z)}\right) - \exp\left\{-\left(\frac{z-240}{L_4(z)}\right)\right\}\right]$$

$$L_4(z) = \begin{cases} 40 + 0.2\,z & 60\text{ km} \leq z \leq 400\text{ km} \\ 120 & 400\text{ km} < z \leq 1000\text{ km} \end{cases}$$

and ($z \geq 1000$ km)

$$\Lambda_5(z) = (1. \times 10^3/z)^3$$

Figure 2 illustrates the variation of electron density at a fixed altitude ($z = 300$ km) as a function of geomagnetic latitude. One can note the decrease in density in the equatorial regions ($\lambda_m = 0°$) with subsequent increases as the auroral zones ($60° < |\lambda_m| < 75°$).

Figure 3 displays the approximate total electron collision frequency $\nu_e(\sec^{-1})$ vs. altitude z(km) based on the previous generalized electron density model at the same three geomagnetic latitudes used in Fig. 1. Here

$$\nu_e(z) = \nu_{ei}(z) + \nu_{en}(z) \tag{3}$$

with [Hanson, 1966]

$$\nu_{en}(z) = 3 \times 10^{-8} N_n(z)$$

and

$$\nu_{ei}(z) = \left[2 \times 10^{-4} + 2.5 \times 10^{-5} \ln \frac{3 \times 10^{10}}{N_e(z)}\right] N_e(z)$$

where

$$N_n(z) = 1 \times 10^{15} \exp\left[- (z - 60)/8\right] \text{ cm}^{-3}$$

III. NUCLEAR-DISTURBED IONOSPHERE AND INNER MAGNETOSPHERE

A high altitude (> 150 km) nuclear explosion can severely disrupt the ambient ionosphere and magnetosphere on temporal scales from seconds to hours and on spatial scales from meters to thousands of kilometers. Typical high altitude nuclear explosions (HANE) evolve in time through several stages in which the local plasma and neutral gas parameters, e.g., density, temperature, magnetic field, etc. can change over several orders of magnitude. At early times, on the order of a few seconds after burst, the ambient magnetic field is severely perturbed with the blast energy, in the form of electromagnetic radiation and energetic particles, coupled to and deposited in the ionosphere and atmosphere. At later times, on the order of a few minutes to hours, the ambient geomagnetic field relaxes to its pre-burst state with the HANE plasma expanding to global dimensions

and finally decaying to ambient values. In order to compute analytical formulae for electron density and collision frequency following a HANE we take typical electron densities in the later time regime. We use electron densities derived from a computer simulation of a large yield (1 MTON) HANE at high altitudes (150 km) over the central Rocky Mountain region of the U.S. [Hain et al., 1985]. The total global electron density resulting from a single nuclear burst can be written, in approximate form, as

$$N_e = N_{e,A}(r,t,\lambda,\lambda_m,l_m,\delta_m,\phi,\rho) + N_{e,N}(r,\lambda_m,l_m)$$

where $N_{e,A}$ is the contribution from the ambient ionosphere as outlined in Sec. 2 and $N_{e,N}$ is the HANE contribution. The nuclear part $N_{e,N}$ can be expressed, to lowest order, in the following form

$$N_{e,N}(r,\lambda_m,l_m) = g_1(r)g_2(\lambda_m)g_3(l_m)$$

$$g_1(r) = \begin{cases} 2.9583333 \times 10^5 \exp\{(r-120)/2.052023\} & 60 \text{ km} \le r \le 120 \text{ km} \\ 4.16667 \times 10^1 \,[3 \times 10^6 - (r - 1850)^2] & 120 \text{ km} \le r \le 2.8717 \times 10^3 \text{ km} \\ 8.15032 \times 10^7 (2.871725 \times 10^3/r)^3 & 2.8717 \times 10^3 \text{ km} \le r \le 3.6 \times 10^4 \text{ km} \end{cases}$$

$$g_2(\lambda_m) = \exp\left[- \{(\lambda_m - \lambda_{mo})/0.034\}^2\right]$$

and

$$g_3(l_m) = \exp\left[- \{l_m - l_{mo})/0.034\}^2\right]$$

where λ_m, l_m are the geomagnetic latitude and longitude, respectively measured in radians from the burst coordinates (λ_{mo}, l_{mo}). Figure 4 gives the total electron density at the burst latitude and longitude as a function of altitude $g_1(r)$ at $t = 300$ sec following the burst simulated by Hain et al. [1985]. As can be seen comparing Fig. 4 with Fig. 1 a HANE can increase the electron density by several orders of magnitude over ambient values.

Fig. 5 displays the electron collision frequencies at t = 300 sec following the burst as a function of altitude. An approximate analytical form for the electron collision frequency can be written:

$$\nu_e(r) = \nu_{en}(r) + \nu_{ei}(r)$$

with

$$\nu_{en}(r) = 5.61 \times 10^{-8} N_n(r) \text{ sec}^{-1}$$

$$N_n(r) = 1 \times 10^6 \exp\{-(r-60)/500\}$$

and

$$\nu_{ei}(r) = \left[34 + 4.18 \ln\left(\frac{1.33 \times 10^{12}}{N_e(r)}\right)\right] \frac{N_e(r)}{1.15 \times 10^6}$$

where $N_e(r)$ is expressed in cm^{-3}. Fig. 5 also indicates that the electron collision frequencies following a HANE can also be increased by several orders of magnitude with respect to ambient values due to large increases in neutral and plasma density.

IV. SUMMARY

In this report we have extended and generalized to both lower and higher altitudes the phenomenological models of Ching and Chiu [1973] and Chiu [1975] for electron density in the earth's ionosphere. In addition, we have analyzed computer simulations of a high altitude nuclear explosion in the ionosphere to develop an approximate model of electron density. Finally, we have derived approximate analytical formulae for electron density and collision frequency as functions of altitude in both the natural and nuclear-disturbed ionosphere and inner magnetosphere.

Appendix A

In this appendix we give the functional forms for the quantities A_i, f_i, P_i, u_i, a_i, p_i, h_i occurring in Eq. (1) as discussed in Chiu [1975]. The global electron density N_e is given in units of 10^5 cm^{-3}. The independent variables are

- z = altitude in km
- t = annual time (days of year) in units of months as measured from December 15 of previous year
- λ = geographic latitude in radians
- λ_m = geomagnetic latitude in radians
- l_m = geomagnetic longitude in radians measured eastward
- δ_m = geomagnetic dip angle in radians
- ϕ = local time in radians measured from local midnight
- ρ = R/100 where R is the monthly smoothed Zurich relative sunspot number

The dependent angular variables are

- δ = solar declination angle defined by $\sin \delta = 0.398 \sin [\pi/6(t - 3.17)]$
- χ = solar zenith angle defined by $\cos \chi = - \cos \lambda \cos \delta \cos \phi + \sin \lambda \sin \delta$
- $\psi(\xi, \eta)$ = seasonal anomaly function defined by $\psi(\xi, \eta) = \xi + \delta \cos \eta$
- ζ = seasonal anomaly function defined by $\zeta = \sin \delta \sin \lambda_m$
- μ, ω = shifted local times with $\mu = \phi + \pi/4$ and $\omega = \phi - 0.873$

The functions listed in Eq. (1) are given in Table A1 with $U_i = S_i(\rho)D_i(\phi, \chi, \delta, \lambda_m, \rho)L_i(\lambda_m, \phi, \rho)\ T_i(t, \lambda, \lambda_m, \phi, \rho)E_i(\lambda_m, \phi, \rho)\Lambda_i(\lambda_m, l_m)\Delta_i(t, \delta_m)$.

The functions listed in Table A1 are as follows:

$$D(a,b) = \exp\{[a + b \ln(1 + 30\rho)][\mathrm{sign}\ (\cos \chi)\cos^{1/2}|\chi|-1]\}$$

where

$$W(b, \xi, \eta) = \exp\{- b[\cos \psi(\xi, \eta) - \cos \xi]\}$$

$$P_3 = [2 + \rho + 0.5 \cos(\phi - 0.873)] \exp\{\cos \psi(\lambda_m, \phi)\}$$

$$\begin{aligned} S_3 &= \sigma(\rho) \text{ if } \rho \leq 1.1 \\ &= 2.39 + 1.53[\sigma(\rho) - 2.39] \sin^2\lambda_m \text{ if } \rho \geq 1.1 \\ \sigma(\rho) &= 1 + \rho + 0.204\ \rho^2 + 0.03\rho^3 \end{aligned}$$

$$D_3 = (0.9 + 0.32\zeta)(1 + \zeta \cos^2 \mu) \exp[- 1.1(1 + \cos \omega)]$$

$$L_3 = (1.2 - 0.5 \cos^2 \lambda_m)(1 + 0.05\rho \sin^3 \lambda_m \cos \pi t/6)L'q$$

$$L' = \exp\left\{3 \cos \left[\frac{\lambda_m}{2} (\sin \phi - 1)\right]\right\}$$

$$q = 1 - 0.15 \exp\{- [(12 \lambda_m + 1.05)^2 + (t/2 - 3)^2]^{1/2}$$

$$T_3 = X(t, \lambda_m, \phi, \rho) + Y(t, \lambda^m, \phi)/S_3$$

$$X = 0.7\left[\kappa + 0.178\ \rho^2 S_3^{-1} \cos\frac{\pi}{3} - (t = 4.3\right] W(\beta, \lambda_m, \phi)$$

$$\begin{aligned} Y = 0.2&\left[1 - \sin\left(|\lambda_m| - \frac{\pi}{6}\right)\left[1 + 0.6 \cos \frac{\pi}{3} (t - 3.94)\right] \cos \frac{\pi}{6} (t - 1)\right. \\ &+ \left[0.13 - 0.06 \sin |\lambda_m| - \frac{\pi}{9}\right] \cos \frac{\pi}{3} (t - 4.5) \\ &- (0.15 + 0.3 \sin |\lambda_m|)(1 - \cos \phi)^{1/4} \cos^3 \psi(\lambda_m, 0) \end{aligned}$$

$$\beta = 1.3 + 0.278\ \rho^2 \cos^2 \frac{1}{2}\left(\lambda_m - \frac{\pi}{4}\right) + 0.051\ \rho^3$$

$$\kappa = 1 + 0.085\left[\cos\left(\lambda_m - \frac{\pi}{6}\right) \cos^3 \frac{\pi}{12} (t - 2) + \cos\left(\lambda_m + \frac{\pi}{4}\right) \cos^2 \frac{\pi}{12} (t - 8)\right]$$

$$\begin{aligned} E_3 = \gamma(0.05, 0.5)&\left[1 + G(\phi, \rho)\right](1 - 0.4 \cos^{10} \lambda_m)(1 + 0.6 \cos^{10} \lambda_m \cos^2 \mu) \\ &\times \cos^8 \lambda_m \cos^{12} (|\lambda_m| - 0.262) \end{aligned}$$

$$G(\phi, \rho) = \left(1 + 0.6\ \rho^{1/2} - 0.2\rho\right) \exp 0.25\left[1 + \cos(\phi - 4\right]$$

$$\gamma(a, b) = 1 + a\left(b - \cos \frac{\pi}{3}\, t + \cos \frac{\pi}{6}\, t\right)$$

$$\Lambda_3 = 1 + 0.1 \cos^3 \lambda_m \cos^2\left(1_m - \frac{7\pi}{18}\right)$$

$$\Delta_3 = \gamma(0.03, 0.5)\left[1 + g(\rho, \lambda_m, t) \exp\left\{ - 18\left(|\delta_m| - \frac{2}{9}\pi\right)^2\right\}\right]$$

$$g\left(\rho, \lambda_m, t\right) = 0.15 - (1 + \rho) \sin^2 \frac{1}{2} \lambda_m \exp - 0.33(t - 6)^2$$

$$f_3 = \exp\left\{ - \left[2.4 + (0.4 + 0.1\rho) \sin \lambda_m\right]^6\right\} \cos^6 \lambda_m$$

$$p_3 = 240 + 75\rho + 83\rho\zeta \cos \lambda_m + 30 \cos(\phi - 4.5|\lambda_m| - \pi) - 10 \cos \lambda_m \cos \frac{\pi}{3} (t - 4.5)$$

$$h_3 = 2H_J(z) \text{ if } z \leq p_3$$

$$= 2H_J(p_3) \text{ if } z \geq p_3$$

$$H_J(x) = 20 + 0.1x$$

Table A1

Functions in Eq. (1)

Function	i = 1	i = 2	i = 3
A_i	1.36	2.44	0.66
a_i	0.5	0.5	1.0
p_i	110.0	180.0	p_3
h_i	10.0	34.0	h_3
f_i	0.0	0.0	f_3
P_i	1.0	1.0	P_3
S_i	$(1 - 1.15\rho)^{1/2}$	$(1 + 1.24\rho + .25\rho^2)^{1/2}$	S_3
D_i	D(2,0)	D(1,30)	D_3
L_i	1.0	1.0	L_3
T_i	$W(0.4, \lambda, \phi)$	$W(0.25, \lambda, \phi)$	T_3
E_i	1.0	1.0	E_3
Λ_i	1.0	1.0	Λ_3
Δ_i	1.0	1.0	Δ_3

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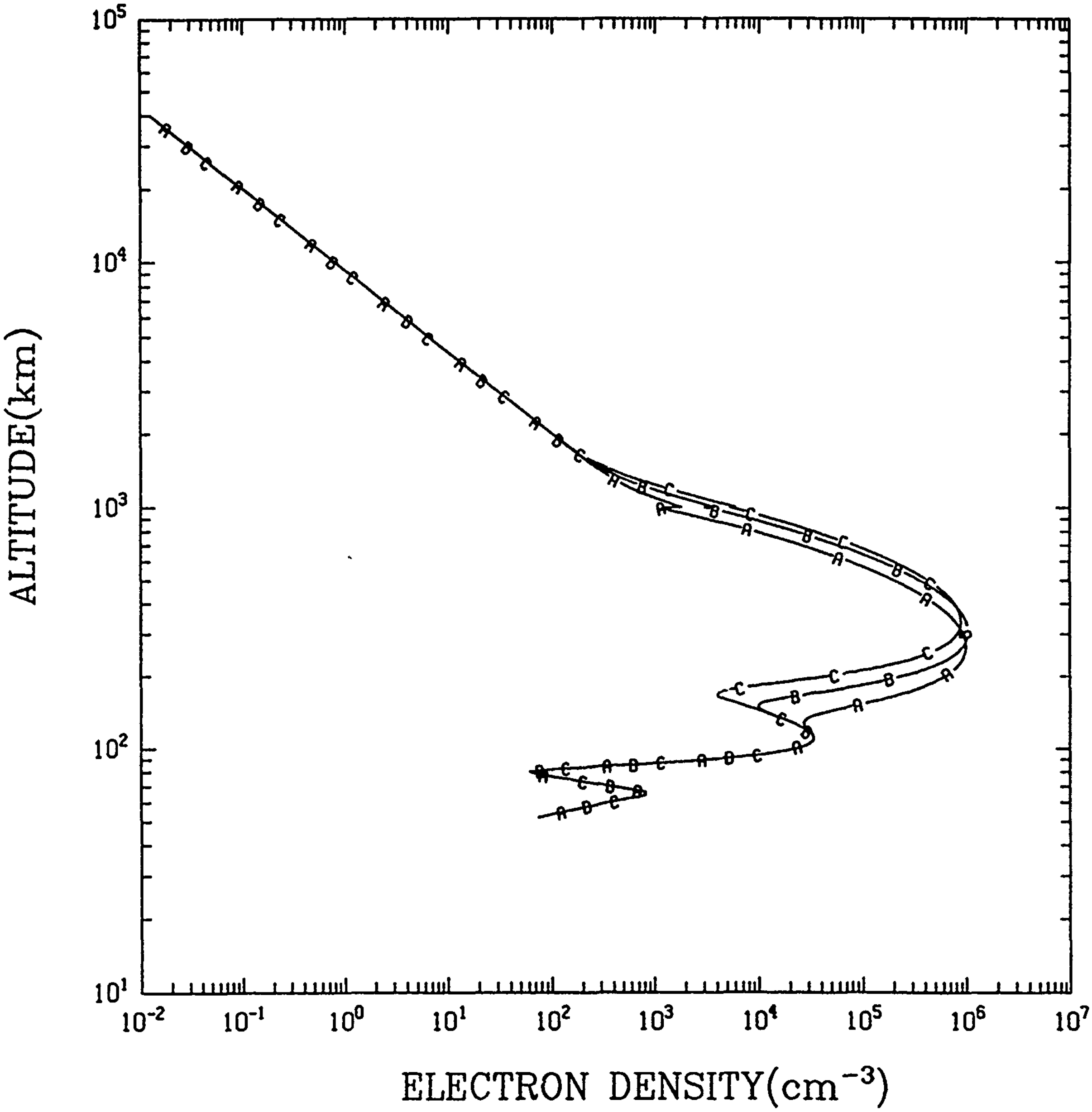

Fig. 1 Plot of electron density in cm^{-3} vs. altitude in km for three different geomagnetic latitudes. Curve A . presents midlatitude (λ_m = 45°), curve B, auroral (λ_m = 60°) and curve C, polar (λ_m = 80°) in the northern hemisphere. Values for the other parameters are: t = 1, λ = 1.2, l_m = 3.1, ϕ = 3.14, p = 1.

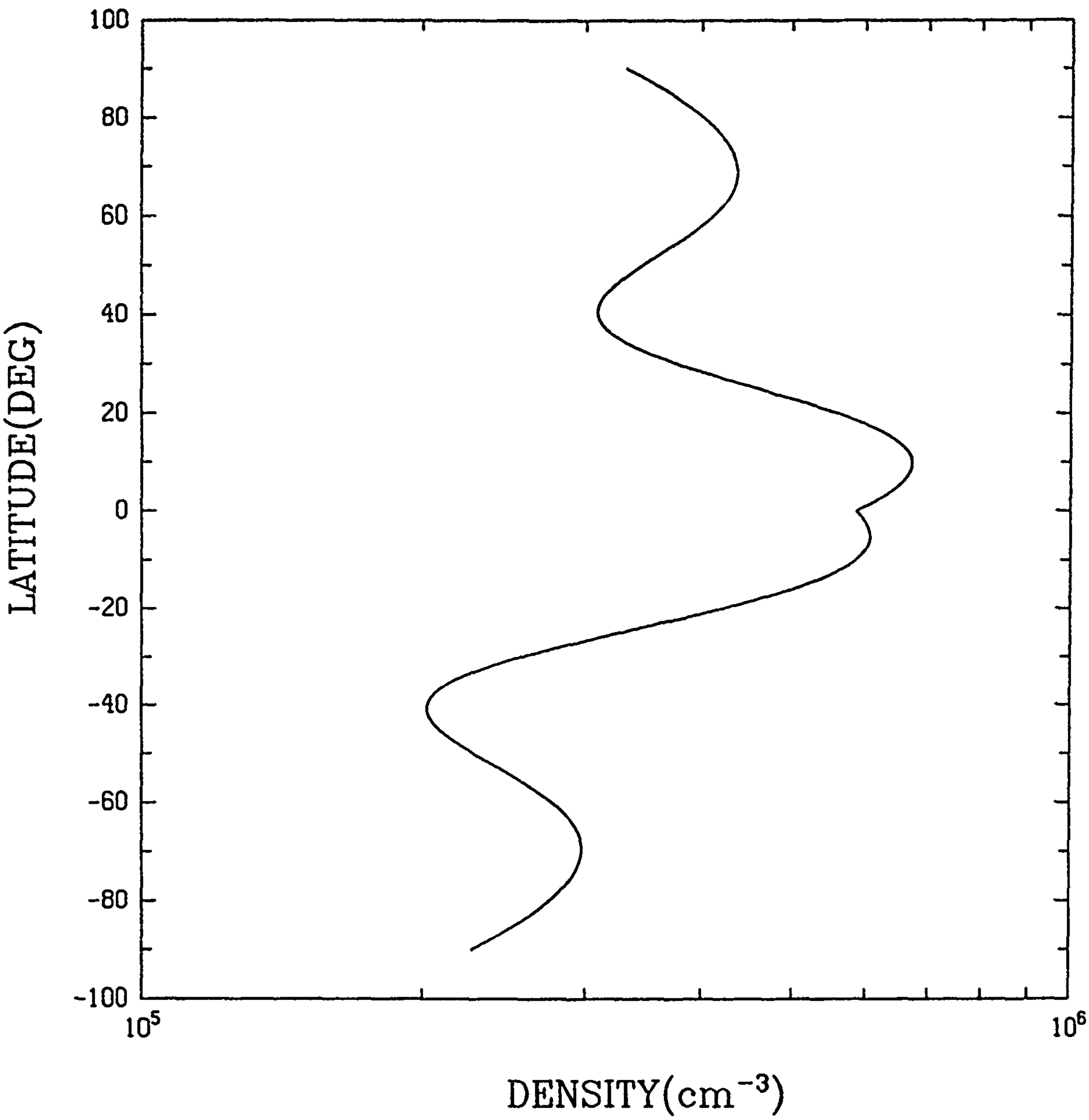

Fig. 2 Plot of electron density (cm^{-3}) vs. geomagnetic latitude at a fixed altitude (z = 300 km) using the same parameters as in Fig. 1.

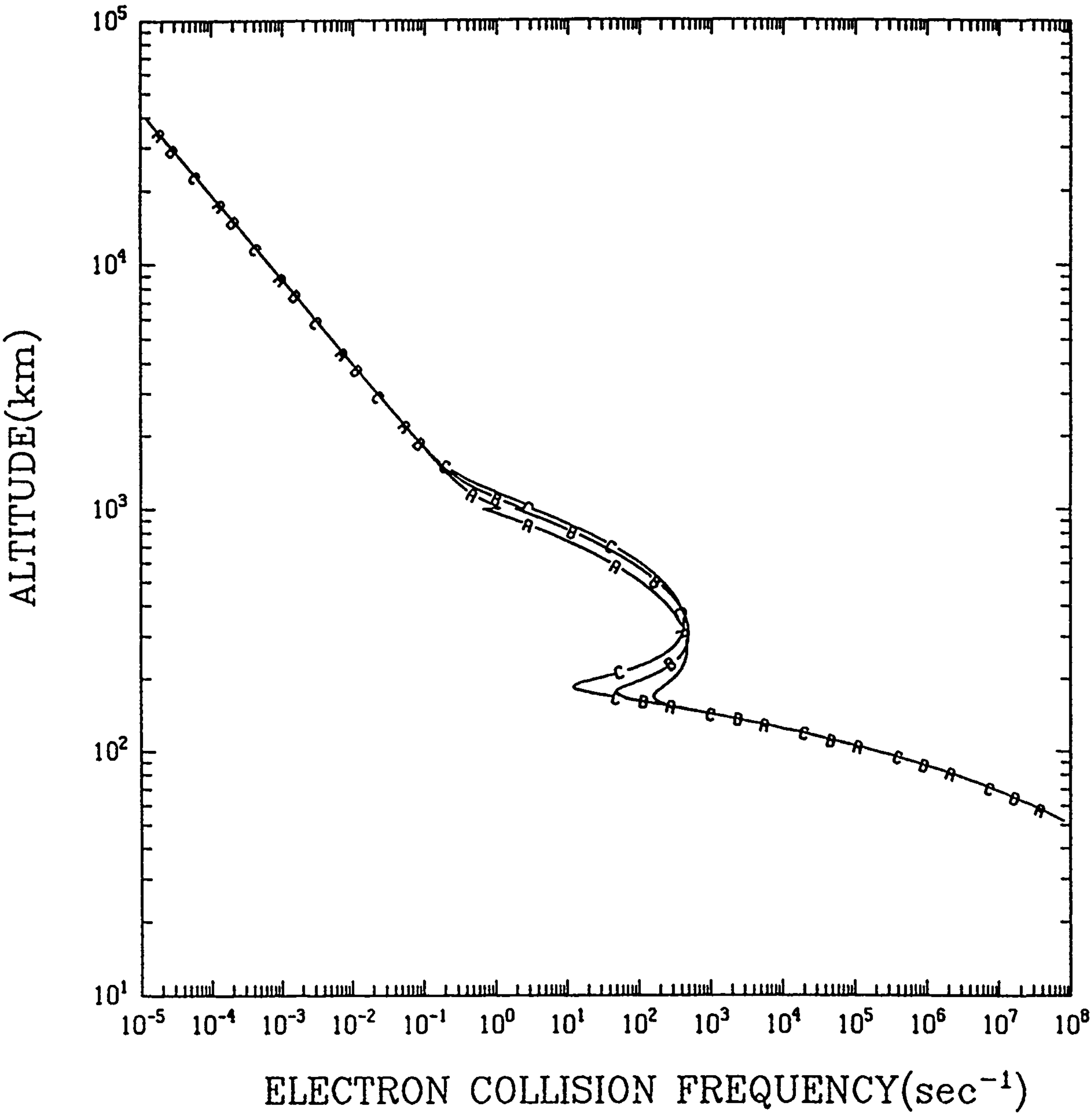

Fig. 3 Plot of electron collision frequency (sec^{-1}) vs. altitude (km) at the same geomagnetic latitudes as shown in Fig. 1.

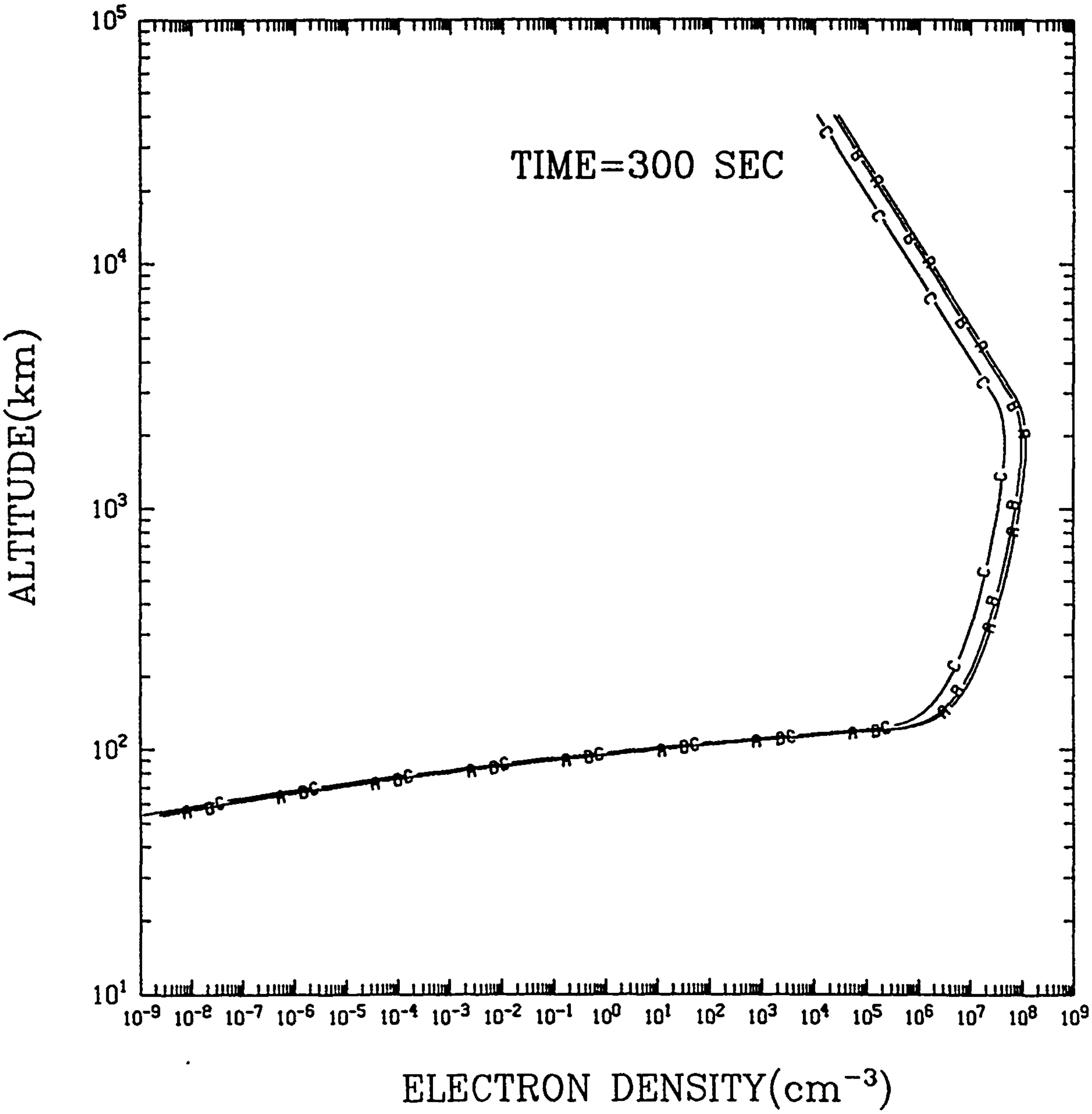

Fig. 4 Plot of electron density (cm^{-3}) vs. altitude (km) for a typical nuclear disturbed ionosphere at t = 300 sec following burst using the parameters from Hain et al. [1985]. Curve A is computed at 20 km from the burst magnetic field line in a direction perpendicular to the magnetic field. Curve B is computed at 50 km while curve C is at 100 km.

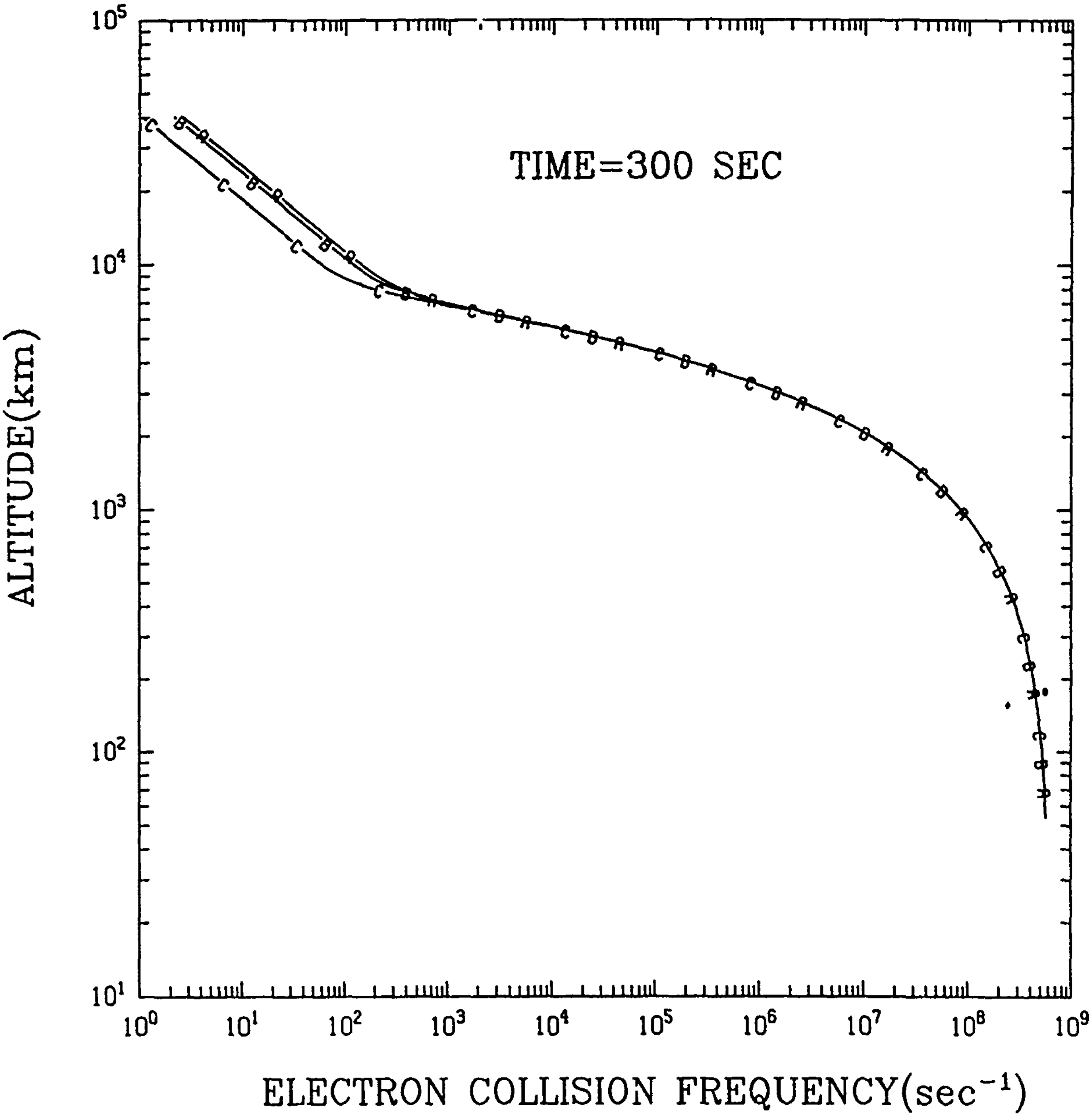

Fig. 5 Plot of electron collision frequency (sec^{-1}) vs. altitude (km) using the same notation as in Fig. 4.

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